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RING SPRING ENERGY DISSIPATORS IN SEISMIC RESISTANT STRUCTURES

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SUMMARY

Ring springs comprise stacks of concentric inner and outer rings with interactive taper surfaces which slide across each other. On the application of external axial load, the wedge action of the taper faces expands the outer rings and contracts the inner ones, thus allowing axial deflection. This paper summarizes results from a prototype steel ring spring and shows that spring behaviour conforms with that predicted from theory. The application of ring springs to holding down bolts on chimmey and other columnar structures is explored. It is suggested that these springs could also be used as horizontal thrusters on bridges and buildings, and in structural bracing members.

INTRODUCTION

The investigation described was prompted by the anticipation that ring spring energy dissipators will have a valuable application in earthquake response mitigation, possibly in conjunction with holding down bolts at the base of column type structures such as chimneys. Typically these structures are held in place by "holding down" bolts which have their lower ends embedded in the concrete foundation. These bolts are usually long and extend through the chimney lower or base flange with the nut at a second bolt hole in a flange higher on the structures, giving an 'elastic' bolt - 'stiff' flange configuration. With appropriate bolt pretension, the fluctuating part of the load resulting from wind gusts can then by reduced so that bolt failure by fatigue is avoided.

However, if the structure is subjected to severe seismic loading, the bolts extend plastically and the chimney rocks on its base flange (Ref.1). When this bolt elongation occurs with the first major seismic load cycle, the structure is free to step unconstrained from side to side until the upper flange or bolt hole impacts against the bolt nuts. The kinetic energy of chimney motion is then transmitted to the bolts as impact loading. This at best will further deform the bolts, but may also result in cleavage (brittle) failure of the already plastically deformed bolts.

The proposed ring spring system will be incorporated with the holding down bolts, and will provide four possible advantages:

(i) The springs take up all the seismic displacement, thus avoiding any damage to the holding down bolts.
(ii) The springs continue to provide constraint, or a holding down force, throughout the seismic event.
(iii) Suitably designed ring springs are capable of absorbing 60% of the seismic energy with each cycle.
(iv) Since neither bolts nor springs are damaged by the seismic load, and the springs recoil to their original length, neither needs to be replaced after the earthquake.

RING SPRINGS

Ring springs comprise a stack of concentric inner and outer rings with interacting tapered surfaces which slide across each other (Figure 1). On the application of external load, the wedge action of the tapered faces expands the outer rings and contracts the inner ones, thus allowing axial deflection (Figure 2). By resolving the taper face forces shown in Figure 3, the following equations are derived:

a) For increasing compressive force

$$P_i = \frac{N(\tan\alpha + \mu)}{(1 - \mu\tan\alpha)} \qquad (1)$$

where N = radial force on one taper face α = taper angle and μ = interface friction coefficient; also

$$N = \sigma\pi A \qquad (2)$$

where σ = ring hoop stress (mean) and A = effective cross-section area of ring. Therefore

$$P_i = \frac{\sigma\pi A(\tan\alpha + \mu)}{(1 - \mu\tan\sigma)} \qquad (3)$$

assuming inner and outer rings have the same effective area i.e. $A = A_1 = A_2$ and $\sigma = \sigma_1 = \sigma_2$

b) For decreasing compressive force

$$P_d = \frac{\sigma\pi A(\tan\sigma - \mu)}{(1 + \mu\tan\sigma)} \qquad (4)$$

c) The total spring deflection

$$\delta_t = \frac{n\sigma(d_1 + d_2)}{2E\tan\alpha} \qquad (5)$$

where d = effective ring diameter, n = total number of inner plus outer rings, and E = modulus of elasticity = $E_1 = E_2$ (assuming inner and outer rings are of the same material).

The resultant force/deflection curve for a ring spring is shown in Figure 4 (schematic). In addition to the strain energy required for elastic deformation of the individuals rings, considerable energy is absorbed in overcoming frictional resistance on the interacting tapered surfaces. From the above equations the slopes of the force/deflection curves for increasing and decreasing load can be obtained, viz.

$\frac{P_i}{\delta_t}$ and $\frac{P_d}{\delta_t}$ respectively. The ratio of these slopes is then:

$$\frac{P_i}{P_d} = \frac{P_i}{\delta_t} \Big/ \frac{P_d}{\delta_t} = \frac{(\tan\alpha + \mu)}{(1 - \mu \tan\alpha)} \frac{(1 + \mu \tan\alpha)}{(\tan\alpha - \mu)} \tag{6}$$

again assuming $\sigma = \sigma_1 = \sigma_2$ and $E = E_1 = E_2$.

It can be seen from equation 4 that P_d becomes negative if $\mu > \tan\alpha$, i.e. the slope P_d/δ_t becomes negative and the spring fails to recoil. Equation 6 tends to infinity when $(\tan\alpha - \mu)$ tends to zero, also $P_i/\delta_t = P_d/\delta_t$ when the interference friction equals zero, i.e. $P_i/P_d = 1.0$.

When the spring system is pretensioned (i.e. the spring is compressed) to a load P_B (Figure 4) and the load is increased to P_A during a seismic cycle, the energy absorbed per cycle is:

$$W_A = \frac{(P_i - P_d)\ \delta}{2P_i^2} (P_A^2 - P_B^2) \tag{7}$$

and the proportion of total cyclic energy absorbed is:-

$$W = \frac{W_A}{W_T} = (1 - \frac{P_d}{P_i}) \tag{8}$$

This is a maximum when P_d/P_i equals zero or when P_i/P_d approaches infinity.

EXPERIMENTAL RESULTS AND DISCUSSION

A prototype ring spring was manufactured with a taper angle of 15 degrees. Inner and outer rings had the same effective area ($A = 93.7\ mm^2$) and were manufactured from the same steel (SKF 280). The effective diameters were $d_1 = 84.70$ mm and d_2 75.55 mm. A total of 11 ring pairs were used to make up the spring ($n = 22$) which was cycled in compression using a universal testing machine. The interacting taper surfaces were lubricated with molybdenum disulphide (MoS_2), secondly by a polyethylene layer, and thirdly by grease. They were also tested in a dry condition.

Typical force/deflection curves are shown in Figures 5 and 6 for lubrication with grease and with the ring surfaces in the dry condition. The slopes P_i/δ_t and P_d/δ_t were obtained from these and similar curves derived with the other lubricants. The ratio P_i/P_d was then obtained from these slopes and the equivalent friction coefficients determined from Figure 7. These coefficients do not necessarily represent absolute values for friction, but are averaged values for the applied test conditions. For example no extraordinary measures were taken to clean the rings prior to testing in the 'dry' condition. However, the 'spiking' shown for both increasing and decreasing force in Figure 6 suggests that interface conditions were changing from static friction to kinetic (sliding) friction on some ring pairs, causing a sudden change to lower friction levels. It is known that the static friction coefficient may be 50% larger than the kinetic coefficient (Ref.2).

The curve for P_d/δ_t in Figure 7 approaches zero (P_i/P_d tending to infinity) when the friction coefficient exceeds 0.25 for the 15 degree taper angle used, i.e. the ring spring will no longer recoil with decreasing load. Obviously this situation is to be avoided in order to retain some holding down force on the structure (e.g. a chimney flange).

The importance of taper angle is shown in Figure 8. With low taper angles (around 10 degrees) spring sticking and non-recoil occurs with interface friction coefficients of less than 0.15, whereas this condition is not encountered until the interface friction coefficient exceeds 0.3 with a taper angle of 20 degrees.

The cyclic absorbed energy, expressed as a percentage of the total cycle energy, for a spring cycling between P_B and P_A (preload and peak seismic load, see Figure 4) is shown as a function of taper angle in Figure 9. For a 15 degree angle approximately 60% of the cycle energy is absorbed when the taper surfaces are greased. This increases to 70% with dry interface surfaces. The absorbed energy is also increased with reduced taper angle (e.g. 70% with greased interface surfaces and a 10 degree taper angle). However the possibility of spring sticking and non-recoil makes either option (taper angle of less than 15 degrees or dry interface) an unacceptable risk. Lubrication with grease is also essential to prevent fretting and/or corrosion of the interface surfaces. Deterioration of this type would promote spring sticking and non-recoil.

The available gap for spring travel (δ in Figure 3) is also affected by the taper angle. For an acceptable diameter tolerance of ± 0.04 mm on each ring (total for two interacting rings of 0.08 mm) the error in the length displacement δ with a 15 degree taper is approximately 0.3 mm, see Figure 10. This is increased to approximately 0.5 mm with a 10 degree taper angle, i.e. a small taper angle makes greater demands on machining tolerance.

CONCLUSIONS

Ring springs appear to have considerable potential as seismic energy absorbers, particularly for use with holding down bolts on vertical column type structures. Data obtained from a prototype steel spring suggests that a taper angle of 15 degrees with the interacting taper surfaces lubricated by grease, offers the best compromise between energy absorption and the need to ensure spring recoil with decreasing load. Close to 60 percent of the seismic energy can be absorbed with each load cycle under these conditions. Since spring recoil is assured, full elastic spring function is retained for subsequent load cycles and the holding down function unaltered.

In practice the springs would have to be preloaded to above the expected wind gust load so that spring deflection would not occur from wind gusts or minor earthquakes. The intent would be to ensure that the springs would only function when subjected to severe seismic load, and could be designed to withstand these major loads without damage to either the spring or the holding down bolts. Each spring assembly could be enclosed in a protective cap to prevent corrosion and deterioration of the lubricant.

Since the spring and bolt assembly no longer conforms to an elastic bolt-stiff flange configuration, the bolts cannot be pretensioned to a degree necessary for the avoidance of bolt failure by fatigue. It would be necessary to specifically design the holding down bolts to withstand cyclic fatigue loads resulting from wind gusts. However, sufficient knowledge exists to enable this design to be carried out effectively and without difficulty.

Other aseismic applications of ring springs could be their use as horizontal thrust resisters on bridges and building structures, and their incorporation in structural bracing members. They could also be used as support dampers for heavy reciprocating engines and other situations of this type.

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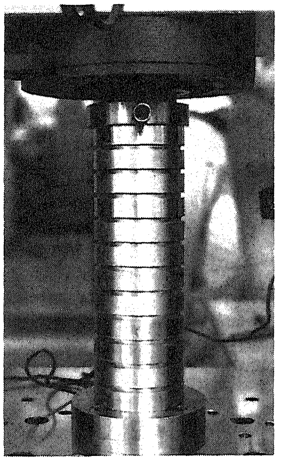

Figure 1(a) Prototype ring spring

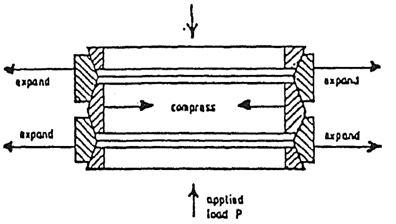

Figure 2. Schematic construction of ring spring

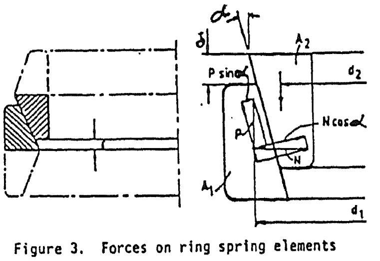

Figure 3. Forces on ring spring elements

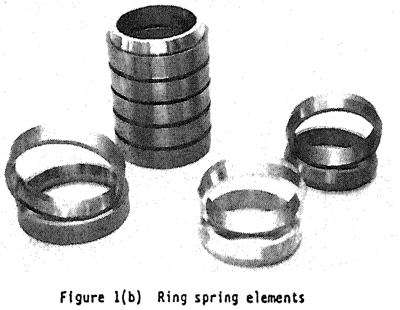

Figure 1(b) Ring spring elements

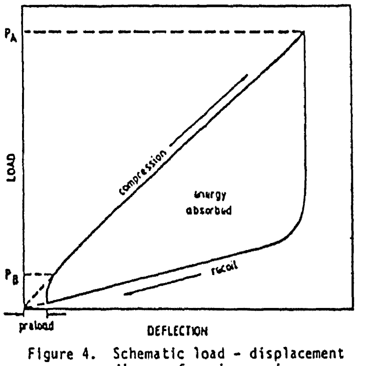

Figure 4. Schematic load - displacement diagram for ring springs

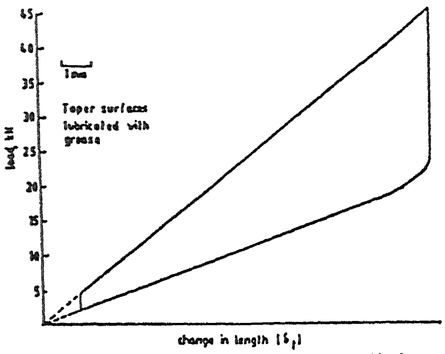

Figure 5. Load - displacement diagram for 22 element steel spring with 15 degree taper angle

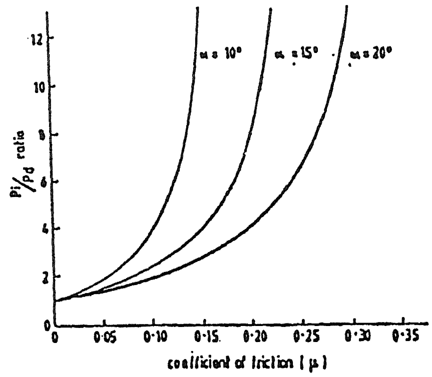

Figure 8. The effect of taper angle and friction on the load ratio P_i/P_d, from Equation 6

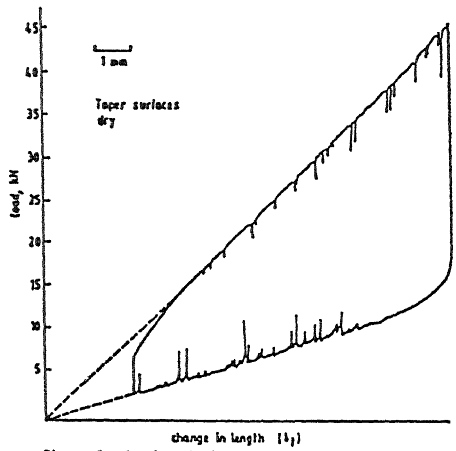

Figure 6. Load - displacement diagram for 22 element steel spring with 15 degree taper angle

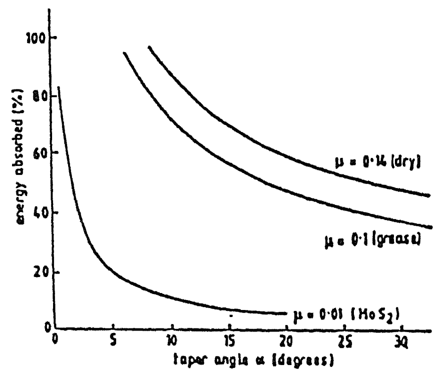

Figure 9. Absorbed Energy from Equation 8 for Three Interface Friction Coefficients

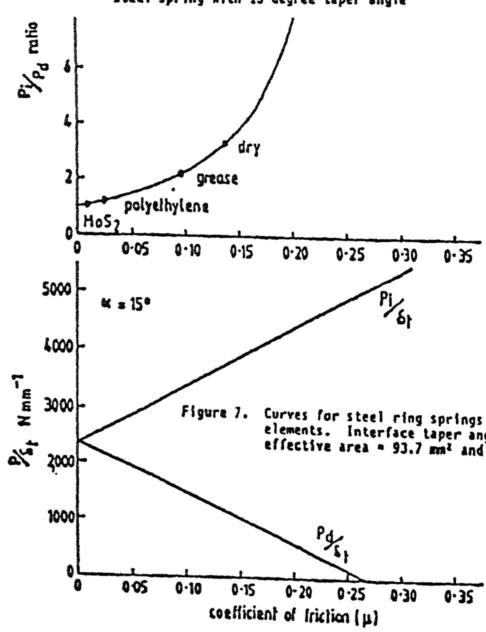

Figure 7. Curves for steel ring springs with 22 active elements. Interface taper angle = 15 degrees, effective area = 93.7 mm² and (d_1 + d_2) = 160.25 mm.

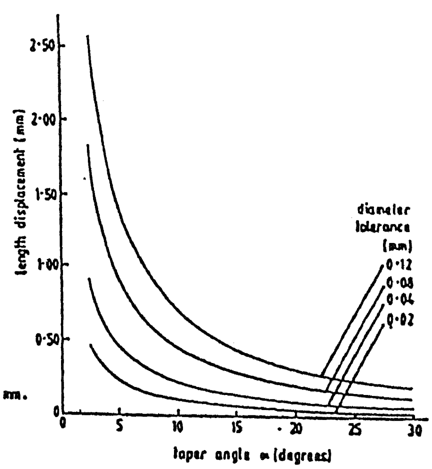

Figure 10. Reduction in spring length displacement resulting from diameter tolerance